TWO CONSTRAINT TYPES: SLOTS & PERCOLATION

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1. Slots in Speech Production Models

1.1 Structure Preserving Errors

There are two types of speech errors - those that involve interactions between two constituents and those that involve single constituents. The interaction errors are structure preserving: they implicate constituents of the same type replacing one another, and the resulting error is structurally well-formed. Interaction errors may be classified as substitutions, exchanges, anticipations, perseverations or blends such as those in (1) respectively:

(1) Interaction Error Types

a. I have an appointment at 10:00 → I have an apartment..., I hate getting up in the morning → I love getting up in the..., there's no right or wrong answer → ...right or left answer

b. central choir → kwentral sire, there’s no dial tone → ...no dole tine, behave in → beyave hin

c. a very tight part four → a very tart -- tight part four, Canadian from Toronto → Tanadian from Toronto, certified Francophone → certifried Francophone

d. just done → just jun, cognitive science centre → cognitive science censer, by redirecting it → by redirectring it

e. shame/pity → shitty, people/person → purple, ten years of age/ten years old → ten years of old

Substitutions (1a) are errors where only one of the constituents in the interaction surfaces in the actual utterance. In exchanges (1b) both constituents surface but in the wrong positions, and in perseverations and anticipations (1c-d) only one of the constituents surfaces but it surfaces twice. Blends (1e) are a type of interaction where some parts of both intentions surface and some parts do not. It is clear from the error outputs in (1) that these outputs preserve structure, that is they are well-formed at some level of analysis.

1.2 Speech Model Slots & Structure Preservation

Speech models have captured the structure preserving nature of these interaction errors with slot and filler mechanisms (Dell et al.,1993; Garrett, 1988; Levelt, 1989; Shattuck-Hufnagel, 1983). These errors are modeled as errors of mis-selection: incorrect fillers have been chosen, but are assigned to correct slot types. The slots (or frames) constrain the interaction possibilities: fillers interact with fillers of the same type.

Slots have two roles in slot and filler production models: i) First, they define those constituents susceptible to interaction. If and only if (iff) a unit is susceptible to interaction with another constituent does it have a slot. ii) Secondly, slots determine what two units may legally interact: only tokens belonging to identical slot types may interact.

In general, slots (or frames) are static, unique types: they are frames into which tokens of their type may be inserted, but they themselves are not subject to the type of error exchanges noted above in (i)-(iii). Noun and verb slots provide places for filler noun and verb tokens, for instance, and these tokens may only be interchanged with tokens of their own type. But slots themselves are impervious to error - only their fillers are susceptible. The mental lexicon can be seen as a repository of tokens of various types. Some are fillers; some are not.

1.3 Types of Slots

Interaction errors like those in (1) can implicate constituents at various linguistic levels, phrasal, lexical and sub-lexical. For instance the following syntactic, morphological and phonological slots determine the types of token constituents that may be inserted into them.

(2) **Syntactic slot errors:** noun, preposition, verb

Nouns: They should have chucked him out at [half time] > They should have chucked him out at [noon], [you'd] call [him] back > [he'd] call [you] back, Go to my locker and get my calculator > go to my [calculator] and get my [locker]

Verbs: You've [got] to [try] to make a play > you've [try] to [got] to make a play, that fans would [pay] to [come] and see > ...would [come] to [pay] and see, [drink] water and [eat] jello > [eat] water and [drink] jello

Prepositions: they love to play [on] grass [in] Australia >... to play [in] grass [on] Australia, Mom will you fill this up [for] me [with] water > ...this up [with] me [for]...,

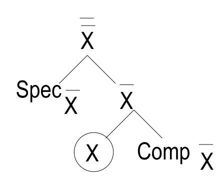

Figure 1
Syntactic Head Slots

(3) **Morphological slot errors:** stem
I like it [cook]ed [quick]ly > ...[quick]ed [cook]ly, Really, the [build]ing of [feet] > ... the [feet]ing of [build] > , A [coach]'s [player] > a [player]'s [coach], to [freeze] [wage]s > to [wage] [freeze]s

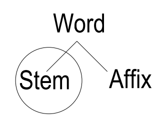

Figure 2
Word Stem Slot

(4) **Phonological slot errors:** syllabic constituent (onset, nucleus, coda)
Onsets: [squ]eeze [fr]esh > [fr]eeze [squ]esh, [ ]Anders [J]arryd > [J]anders [ ] Arryd, [c]entral [cho]ir [kw]entral [s]ire,

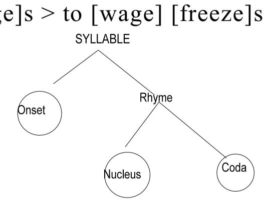

Figure 3
Sub-Syllabic Slots

Nuclei: r[oo]f sl[o]pes > r[o]fe sl[oo]ps, f[ee]t m[o]ving > f[uw]t m[ee]ving, f[i]sh h[oo]k >f[oo]sh h[i]ck, P[a]t Sm[ar]t > P[ar]t Sm[a]t
Codas: Lloy[d] Mo[s]eby > Lloy[z] Mo[d]eby, pa[ss] ou[t] >pa[t] ou[s], wi[th] u[s] > wi[s] u[th]

1.4 How Slots Account for Rare Interaction Errors:

The syntactic, morphological and phonological slots listed in (2) - (4) are regularly subject to error in spontaneous utterances. On the other hand, we find that errors which implicate sub-lexical sequences such as the rhyme (VC), word initial CV sequences, and other (sometimes non-contiguous) sequences are quite infrequent. These infrequent types are exemplified in the errors in (5):

(5) **Rare sub-lexical exchanges**
Rhyme: I don’t care which > ...kich where, lead the way > lay the weed, spice racks >spack rices, Swedish Finns > Swinnish Fedes
CV: lost and found > foust and lond, pussy cat > cassy put, I want some too please > ...plea toos
Other: pepper shakers > shecker papers, the boundaries are fuzzy > the buzzies are foundary, skate sharpening > shape skartening

The errors in (5) preserve input structure in the output, and the exchanges involve seemingly identical sequence types. In other words, like the other frequent interaction errors above in (1), these rare types of interaction are structure-preserving errors. Does this mean that there are slots for these various sub-lexical sequences? With the exception of the rhyme, the sequences do not appear to be constituents (although “rest-of-word” has been proposed (Shattuck-Hufnagel, 1987)).

First let us consider the rhyme errors. Most phonologists (e.g. Fudge, 1987) but not all (e.g. Clements & Keyser, 1983; Davis, 1989) include a rhyme in the syllable. Indeed Dell (Dell *et al*, 1993) includes the rhyme as a slot in his production model on a par with the other syllabic constituents. Clearly it is not parallel, however, as it is not regularly subject to mis-selection (either naturally or experimentally as will be illustrated below). However, the fact that it is sometimes subject to error, as are the other (sometimes non-contiguous) sub-lexical sequences illustrated in (4), means that production models must be able to generate them in some well-motivated way; proposing a plethora of slots to correspond to the sequences rarely subject to interaction would be at best *ad hoc*.

There is good evidence for distinct levels in language production (Caramazza, 1997; Garrett, 1980, 1988; Laubstein, 1999c, ; Levelt, 1989). In models with serially related levels these rare errors can be easily generated. They involve mis-selection errors at two distinct levels in the serially ordered process: the level where morpheme stems are assigned to their slots, and the level where the syllabic constituents, onset, nucleus and coda are assigned to their slots. Errors at each of these levels are frequent and there is nothing to prevent an error occurring at both levels - first the one, and then the other. Serial models predict the occurrence of such compound serially overlapping errors. The process is illustrated in (6) and Figures 4 & 5.

(6) Generating rare compound errors

morpheme stem exchanges (cf. the errors in (2) above): lead the way > way the lead, lost and found > found and lost, pepper shaker $]_{plu}$ > shaker pepper $]_{plu}$, the boundary $]_{plu}$ are fuzzy > the fuzzy $]_{plu}$ are boundary, skate sharpening > sharp skate $]_{en}$ $]_{ing}$, I want some too please > ...please too

onset, coda, nucleus exchanges (cf. (4) above):

onset: way the lead > lay the weed, the fuzzy $]_{plu}$ are boundary > the buzzy $]_{plu}$ are foundary

coda: found and lost > foust and lond, ...please too

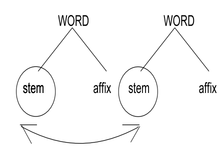

Figure 4
Word Stem Error

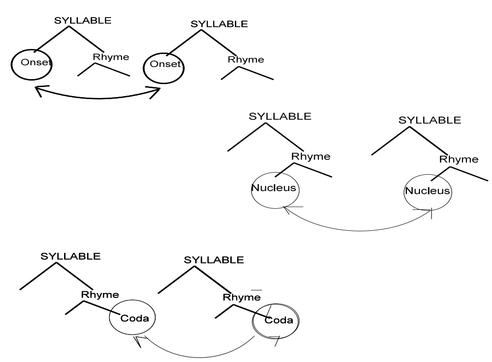

Figure 5
Sub-Syllabic Errors

> ...plea toos
nucleus: shaker pepper > shecker paper $]_{plu}$, sharp skate $]_{en}\,]_{ing}$ > shape skart $]_{en}\,]_{ing}$

Notice that affixes are regularly stranded in the morpheme stem errors in (2) above, just as they are in these complex two-level errors in (6).

It appears then that we can generate all types of structure preserving errors with well recognized slot types. In fact none of these errors require the postulation of any slots not already referred to in (2)-(3) above. This way of generating the rare errors also predicts correctly that so-called rhyme (VC) errors, although rare, will be more frequent than CV errors. This is due to the fact that onset errors are more frequent in natural corpora than coda errors: the spurious rhyme errors involve the stem exchange followed by the commonly occurring onset exchange, whereas the CV errors involve the stem error followed by the less frequent coda exchange.

1.5 Non-Interaction Errors in Speech Models

Constituents not subject to interactions with other constituents of their type are not assigned to slots and hence they can not be mis-assigned. For example, although grammatical morphemes such as tense, aspect and plural may be found shifted out of position they are not subject to exchange interactions. Speech models achieve this effect by having no slots labelled "grammatical morpheme". Such non-structure-preserving errors involve the misplacement of some single (usually) closed class constituent as seen in (7a-b).

(7) Non structure-preserving errors:

a. banana bread's something I like > banana's bread something...)**;** getting the street**s** wet > getting the street wet**s;** so quick thought**s** about what happened > so quick thought about**s** ...

b. I'll help you **un**load > I'll **un**help you load; Remind me 'cause I could **quite** easily forget >...I **quite** could easily forget; without **it** done > with **it** out done; the puck up the **whole** ice > the **whole** puck up the ice; just countin' them **up** > ...**up** them; There could **well** have been a coverup > There **well** could have...

Non-structure preserving errors like those in (7a) implicating grammatical morphemes have been modeled as involving tags associated with particular frames, and these tags show up in wrong positions when such morpheme tags are spelled out in their NP or VP (Garrett, 1980).

2 Foot Constraints

2.1 Natural Error Evidence

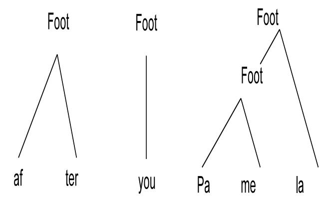

Figure 6
English Feet

Given the errors in (3) above it is quite clear that the syllable provides slots parallel to morphological and syntactic slots. Interactions which involve sub-lexical segments and segment sequences are constrained by the syllable and, in particular, its lowest level sub-syllabic constituents. The only constituents that are regularly subject to interactions are onsets, nuclei and codas and they do not get realized in wrong positions like the closed class items in the errors in (7), for instance. Onset tokens interact with other onset tokens, as do coda and nuclei tokens. Onsets do not interact with codas, even though they both implicate consonants. The interactions are structure preserving. The syllable constrains sub-syllabic interactions: in other words, it provides slots for its sub-syllabic constituents, onset, nucleus and coda. What about the syllable's superordinate prosodic structure, the foot?

Not only do errors provide evidence of prosodic constraints due to the syllable, but there is also evidence for constraints due to the stress foot; and the evidence suggests that it too may have the function of a slot. For instance, the foot constrains mis-selection errors: when two items interact they are from equivalent foot branches: they either are both from the strong branch of a foot, or both from the weak branch of a foot. For instance, the sub-lexical errors in (4) above all involve interactions between strong branches (the most common type) whereas the errors, *Canadian from Toronto >Tanadian from Toronto* and *minor dental work > minol dentar work* implicate the weak branches of feet. This foot-based constraint is true of word blends too. For example, in the following two blends the onset replacements implicate two strong branches: *rat/weasel > reasel* (not **wearel* or **zat*), whereas in *mature/adult > madult* the branches are both weak (not **amult* or **dature*).

English is distinct from a number of languages in that its unstressed vowels are all reduced central vowels and it has been suggested that the brain may store stressed syllables and unstressed syllables separately. In many languages the quality of the vowel remains unchanged even though its length, intensity and/or pitch may vary between stressed and unstressed versions of the same vowel. This raises the question as to whether the foot constraint isn't just an artefact due to the nature of the English unstressed vowels. Apparently this is not the case. An analysis of Swedish and Italian word blends (Laubstein, 2002) mirrred the English data. Unstressed (weak) interacted with unstressed (weak) and strong with strong. Not only are blend **interactions** constrained by the foot but so are word blend **outputs**. They invariably maintain the foot structure of one of the inputs, as can be seen in the errors in (1e) above.

To sum up then, metrical structure is preserved in sub-lexical errors and hence the outputs are metrically well-formed. Is the foot then a slot? As discussed above in section 1, the slot has two distinct roles in production models: i) it defines what units will be subject to interactions, i.e. the slot determines the nature of fillers that can be selected, and hence mis-selected, and ii) it constrains the interactions to fillers of the same type. Clearly the foot has the latter slot function; it constrains what units may interact as just illustrated. The question is whether it also has the former role; does it also define a set of interacting units? That is, is it a slot that provides its constituent syllables as fillers - fillers that will be subject to interaction with other syllable fillers? As a foot constituent the syllable may play a filler role. If so, we should frequently find whole syllable exchanges, but do we?

In natural error corpora, when whole syllables exchange, we find that they are in fact ambiguous: that is, they can be analyzed as either syllable or morpheme exchanges. For instance, in a number of the errors in (2) above and in the errors *Rockefeller > Fellerocker* and *the corner of Walkley and Bank > the corner of Bankley and Walk,* the constituents which are subject to exchange are ambiguously either syllables or morpheme stems.

However, there are some errors which **may** implicate whole syllables: this unambiguous group is a small set of word blend errors. Almost all blends can be analyzed as substitutions of sub-lexical onsets, nuclei or codas, or of stems (ambiguously affixes) such as the errors in (8) (Laubstein 1999b):

(8) Frequent types of blend errors

onsets: pity/shame → shitty, hot/sunny → sot, dive/job → jive
nuclei: quick/fast → quack, hustle/hurry → hurstle, trip/job → trop
codas: minor/trivial → minol, muggy/humid → muggid, switched/changed → swinjed
stems: human resources/personnel → humanel, November 11/ Remembrance Day → Novembrance Day, momentary/instantaneous → momentaneous, edited/annotated → editated, unbelievable/remarkable → unremarkable

The types in (8) are the norm; however, there are a very small set of errors that do not implicate either syllabic sub-constituents or affixes as can be seen in the errors in (9). These may implicate feet or syllables.

(9) Rare blend errors

aggravates/intensifies → aggrifies, nullifies/negates → nulligates, complicate/simplify → complify, recognize/reflect → recoflect, appearance/impression → impearance, parallel/corollary → corallel,

Since the slot/filler mechanism is the formal device in production models for predicting what constituents will be susceptible to interactions, and for constraining the interactions to constituents of the same type, by *Occam's Razor* it would be nice to be able to incorporate the foot-based constraints and the possible syllable interactions in the same way: namely by including the constrainer - i.e. the foot, as a slot which gets filled by token fillers of the appropriate kind - namely by syllables. However, as just discussed, the natural error data are not compelling with respect to the foot's role as a slot for its constituent syllables; and as we will see the experimental data mirrors the natural errors in this regard.

3 Two Experiments

3.1 The Rhyme

There are numerous problems associated with natural corpora of errors (Cutler, 1981) and hence it is incumbent upon production modelers to experimentally test any hypotheses based on these data. Sub-lexical errors elicited experimentally using various different techniques produce errors similar to those found in natural speech contexts (Stemberger, 1992). For this reason it is possible to experimentally test hypotheses based on natural errors. For instance, the sub-lexical syllabic constituents that are regularly subject to error in natural corpora are the onset, nucleus and coda and earlier experiments illustrate that these are also the constituents subject to error in experimentally elicited corpora (Laubstein, 1990; Stemberger & Treiman, 1986).

Using the SLIP error elicitation method (Motley *et al*) a recent experiment addressed the rhyme's status compared to other sub-lexical sequences (Laubstein, to appear). The experiment found that the experimentally elicited errors mirrored the natural data. That is, Onsets, Nuclei and Codas were subject to exchange, anticipation and perseveration errors but the #CV sequence and the VC# (Rhyme) sequence were relatively unsusceptible to error. Indeed, statistical tests indicated that these two, #CV and VC# sequences behaved like each other and not like word final Sonorant Obstruent or Obstruent Obstruent codas, or the various possible vowel nuclei (V, VG or Vr). On the other hand theses constituents were statistically indistinguishable from one another.

3.2 The Foot

A second experiment (Laubstein 2004) addressed the question of whether feet, like syllables, provide slots in language production. Using the same method as in the first experiment an attempt was made to produce interactions between whole syllables, both stressed and unstressed.

The SLIP method involves biasing subjects to pairs of sounds, or sound sequences, in a particular order *a b* , and then asking subjects to repeat the particular pair in the opposite order. Subjects silently read pairs of words or non-words on a monitor until they hear a beep and simultaneously see a set of question marks. At this point they are to repeat the pair they have just seen out loud. These target cued items will have the order of the sequences of interest reversed. Since this experiment was interested in the sequences CV, VC, Syllable (SYL), stressed Syllable (SYL.F(oot)), CC# (coda) and Vr (nucleus) these sequences were primed. The following sample items illustrate some experimental items with their four bias pairs followed by their cued targets with the sequence of interest reversed.

(9) Sample experimental items

CV (ba-co) bad coot, bat cool, bam coed, bath couth, coop back ????
VC (ack-iff) rack biff, zack ziff, lack liff, sack siff, diff mack ????
Vr (ar-aCe) farth face, parth pace, karth lace, barf tace, dake sart ????
CC (OS)# (mp-dge) slump budge, damp fadge, crimp hidge, zemp zedge, dudge frimp ????
CC (OO)# (sk-p) bisk bip, lask lap, busk mup, sesk rep, dup gask ????
SYL.F (pine-cate) caspine marcate, tarpine remcate, limpine selcate, shalpine forcate, halcate melpine ????
SYL (per-ckle) dupper cackle, fapper sickle, repper teckle, bopper mockle, suckle tupper ????

The analysis compared numbers of errors which implicated entire constituents and numbers of errors where only parts of constituents were subject to error. The results strongly supported the experimental hypothesis: CC# codas, Vr nuclei are non-distinct from one another and they are significantly different from the non-slots, CV, VC, SYL.F and SYL.

It is noteworthy that the experiment mirrored natural data in that the SYL and SYL.F items produced errors but they did not implicate whole syllables as units; instead they produced onset and coda errors, and the onset errors were more frequent than the coda errors. This result attests to the ecological validity of the SLIP technique.

It appears that the syllable's role is limited to its role as provider of slots for its sub-constituent onsets, nuclei and codas. It itself is not a filler for a slot. Syllables provide slots but feet do not.

4 Percolation Phenomena

4.1 Formally Capturing Foot Constraints

Since the syllable as a unit is not susceptible to error, foot constraints can not be handled parallel to the other interaction constraints. Nonetheless, from a formal point of view, it seems fairly simple to incorporate foot constraints into production models. The branch features, namely Strong and Weak, could be allowed to percolate down to all syllables depending on their foot attachments. Sub-syllabic constituents would be labeled as S-onset, S-nucleus and S-coda (W-onset, W-nucleus and W-coda) and sub-lexical interactions would be constrained appropriately. For instance see the word "central" in Figure 7 where S and W from the strong and weak branches of the foot percolate to the syllabic constituents susceptible to error.

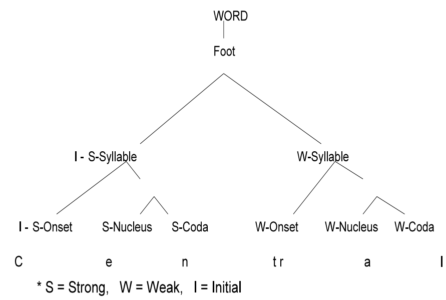

Figure 7
Percolation of S W & I

4.2 Word Onset Salience

It may be that percolation is also the appropriate device for accounting for word-initial effects. It is well known that word onsets are more susceptible to error than other word positions. It also seems to be the case that word onsets are relatively less susceptible to error when words or word lists are the primed materials in experiments (Shattuck-Hufnagel 1987, Laubstein 1999a); it seems that they are more prone to error when the target words have to be assigned to phrases. It is also well-known that word onsets are the most salient word parts in Tip Of the Tongue (TOT) states. Stress and number of syllables are also often accessible to people in TOT states (Brown & McNeill). These data suggest that metrical structure and word onsets are the pertinent features of lexical items at the initial look-up in the production process. The salience of word initial onsets could be formalized as a percolating feature ("Initial") attached to a metrical skeleton. Perhaps word onsets are susceptible to error at two points in the production process: i) when they are used in the initial word selection look-up and ii) when words are finally fleshed out with all their segments. (See Levelt for details on this double lookup and Laubstein 1999c with supporting evidence.) This would explain why word onsets are most susceptible to error: being selected twice they are susceptible twice. It would also explain why word onsets, in certain experimental situations, are less error prone.

4.3 Metrical Skeleton

It is also noteworthy that metrical structure is inviolate even when segmental content is violated. Assignment of a metrical skeleton may be appropriate when accounting for the fact that stress appears, in some cases at least, to belong to structure and not to segments *per se*. Correct stress position is maintained when segments are exchanged with other segments: the segments which should get the stress have moved out of their correct stress position and they no longer get the stress; the usurpers get it. For instance, *ROCKefeller* > *FELLerocker* and not **felleROCKer.* The same is true in higher level exchange errors such as *You've got to TRY to make a play* > *You've try to GOT to make a play.* These errors illustrate that metrical structure is independent of segmental content. When syntactic, morphological or phonological interaction errors occur metrical structure remains intact.

4.4 Grammatical Morphemes

As mentioned above, grammatical morphemes have been modeled as tags associated with their phrases (Garrett). This accounts for the fact that they can be spelled out in incorrect positions, but they cannot be exchanged with one another. It would seem that a tag is essentially a feature (e.g. tense, plurality) that is associated with its phrase and must percolate to its host head. It is not surprising that the formal devices appropriate to one phenomenon, i.e. stress, are appropriate for another unrelated phenomenon, i.e. the attachment of grammatical morphemes to their heads. It would be surprising if formal devices were limited to single types of phenomena: Occam's Razor would predict that if percolation is needed for accounting for one phenomenon (metrical constraints) it will likely be needed for the account of some other phenomenon, perhaps the attachment of grammatical morphemes.

4.5 Problems

There are, however, word stress errors which are not obviously accountable using the metrical skeleton device described above. These errors seem to be a type of blend error. Blends are errors which involve two competing intentions and parts of both of them surface in the error output. Stress errors blend derivationally related words . The metrical structure of one word is chosen and it is associated with the segmental content of its derivational relative. For instance in the error *adMINistrative* > *adminiSTRAtive* we find that the foot structure fits *adminiSTRAtion* and not *adMINistrative.* However, although in this case the competing intentions have the same number of syllables they frequently do not. For instance in the errors *certifiCAtion* > *cerTIFication* (c.f. *cerTIFicate*) and *psyCHOlogy* > *psychoLOgy* (c.f. *psychoLOgical*) we find that the chosen metrical structure may have fewer or more syllables than the intended segmentally spelled out word. It is not clear how metrical skeletons and percolation could handle these.

Clearly, how stress is formalized in language production awaits an extensive analysis: however, it seems clear that foot constraints cannot be handled by slots and some other formal device is required: percolation looks promising.

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